INVESTIGATION OF THE INFLUENCE OF PVD COATINGS FOR DRY GROOVE MILLING

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This paper deals with the benefits of PVD coatings applied to HSS three edges end milling cutter. Three types of PVD coatings ((Al,Ti)N, (Al,Ti,Cr)N and nanocomposite nACo) were used to extend the tool life. The coatings were synthesized by a cathodic-arc deposition process. Machining was carried out on the vertical milling machine FB 32V without using process liquid. Set up cutting conditions were constant throughout the machining and tool steel called as Stabil steel DIN 90MnCrV8 (W. Nr. 1.2842) was used as workpiece material. The aim of this experiment was to compare coated and uncoated HSS milling cutters and find out the benefits of PVD coatings during groove milling. The monitored parameters were force loading measured by piezoeletrical dynamometer Kistler 9257B and flank wear measured by tool microscope Alicona.

KEYWORDS

high-speed steel, groove milling, PVD coatings, force loading, flank wear.

1 INTRODUCTION

High performance dry machining is one of major trends in modern manufacturing and it is very typical for technologies which are working with interrupted cut – milling. The most widely used materials for production of milling cutters are cemented carbides (monolithic or in the form of cutting inserts) [Humar 2008], but they cannot be used for all cutting operations. High-speed steel (HSS) milling tools exhibit higher toughness then cemented carbides and for this reason they are still used for production monolithic milling cutters [Forejt 2006]. Chemical composition, heat treatment and, at present, the most significant very hard coatings have the greatest influence on their mechanical properties [Kovalev 2000].

Physical Vapour Deposition (PVD) is used for deposition coatings on HSS cutting tools because of lower temperature (450-600)°C comparing to Chemical Vapour Deposition (CVD) where the temperature is much higher (1000-1200)°C [Mattox 2010]. The first reason why only PVD process can be used for deposition coatings to the HSS tools is the heat treatment, the temperature of deposition coatings cannot by higher than the temperature of tempering (about 500-600°C). The second reason is that milling is an interrupted cut and therefore PVD coatings are used, because the blade is subjected to greater shocks [Xu 2014]. The PVD coatings on HSS tools are synthesized by a cathodic-arc deposition process as a monolayer or multilayer [Cselle 2013].

It is generally known that PVD coatings increase mechanical properties – for example hardness, wear resistance, maximal application temperature and thus they extend the tool life. High performance dry groove milling generates severe cutting conditions associated with high temperature and stress within cutting zone. Coatings based on Al, in our case (Al,Ti)N, (Al,Ti,Cr)N and nanocomposite nACo are recommended for groove dry milling, because they can withstand temperatures up to 900°C or higher (coating nACo). The coated HSS milling cutters are used for machining of wood, plastic, nonferrous metals and low-alloy steels [Jaros 2012].

2 EXPERIMENTAL PROCEDURE

The main goal of this experiment was to compare coated and uncoated HSS three teeth end milling cutters and to identify the benefits of PVD coatings during groove milling of tool steel DIN 90MnCrV8 (W. Nr. 1.2842). Monitored parameters were force loading and flank wear. Dynamometer Kistler was used for measuring force loading and tool microscope Alicona was used for measuring flank wear.

2.1 Cutting tools

Four kinds of the HSS Co8 end milling cutters (Ø18 x92mm; see Fig. 1) were used for groove milling (producer, ZPS – Frezovaci nastroje, Zlin, Czech republic) [ZPS-FN 2015]. Three of them were deposited by PVD coatings (producer Liss Platit, share company, Roznov pod Radhostem, Czech Republic). The coating was synthesized by a cathodic-arc deposition process using Al, Ti and Cr cathodes. PVD coatings (Al,Ti)N and (Al,Ti,Cr)N are monolayer and nACo is nanocomposite layer. The temperature of deposition of all coatings was about 450°C [Jaros 2015]. Properties of all synthesized PVD coatings are shown in Tab. 1.

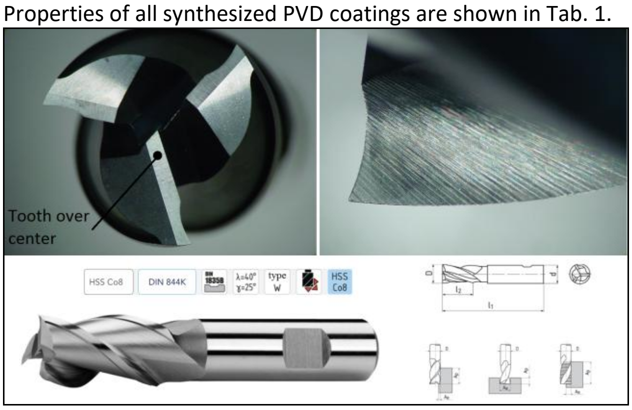

Figure 1. Uncoated HSS Co8 end milling cutter.

Type of coating	Color	Nanohardness [GPa]	Thickness [μm]	Coefficient of friction (against carbon steel) [-]	Maximal application temperature [°C]
(Al,Ti)N	black	33	2-4	0.70	850
(Al,Ti,Cr)N	gray-blue	34	2-4	0.55	900
nACo	purple-black	45	2-4	0.45	1200

Table 1. Physical properties of the deposited PVD coatings [Liss 2015]

2.2 Material of workpiece

Low alloy tool steel DIN 90MnCrV8 (W. Nr. 1.2842) was used; it is called as Stabil steel. This steel is often used for basic cutting and banding tools and measuring gauges [Bolzano 2017]. Dimensions of the workpiece (pre-machined after annealing) were 150x80x30 mm (one workpiece was used for each tested milling cutters). Hardness of used steel was 229 HB (after annealing), the microstructure was not observed. Chemical composition is shown in Tab. 2.

Chemical composition [weight %]	C	Si	Mn	P	S	Cr	V
1.2842	0.89	0.22	1.92	0.019	0.006	0.34	0.08

Table 2. Chemical composition of tool steel DIN 90MnCrV8 (1.2842) [Bolzano 2017]

2.3 Cutting conditions

The groove milling was carried out on three-axis vertical milling machine FB 32V (producer TOS Kurim) without using cooling process liquid, so it was dry machining. Set up cutting conditions were constant during machining (see Tab.3). The clamping of the workpiece and milling cutter are shown in Fig. 2.

Figure 2. The experimental procedure, clamping of tool and workpiece.

Cutting condition	variable	value
Cutting speed	v_c [m/min]	40
Feed speed	v_f [mm/min]	160
Feed per tooth	f_z [mm]	0,075
Axial depth of cut	a_p [mm]	3
Radial depth of cut	a_e [mm]	18

Table 3. Cutting conditions for the experimental groove milling

The primary monitored parameter was force loading of the workpiece generated by milling cutter. The force load was measured in three axes by the dynamometer KISTLER 975B equipped with eight-channel amplifier 5070A. Dynoware software was used for data processing (see Fig. 3).

Figure 3. The Kistler data acquisition and processing [Jaros 2015]

The dynamometer senses reactions induced by cutting tool while removing chip during milling in the Cartesian coordinate system (Fx, Fy, Fz) what can be transformed to machining coordinate system (Fc, FcN, Fp), depending on the angle cutter [Jaros 2015]. The sampling frequency was set up to 10 000 Hz and force load was measured for each tenth cut. Basic distribution of force load of groove milling is shown in Fig. 4. Total force F is calculated according to the equation (1) [Forejt 2006].

$$F = \sqrt{Fx^2 + Fy^2 + Fz^2} \quad (1)$$

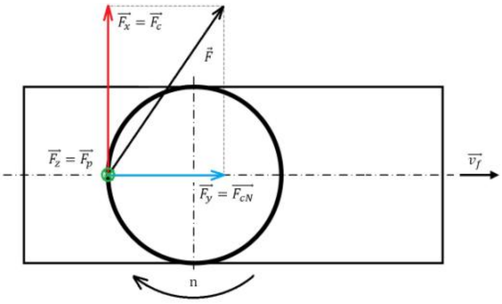

Figure 4. Basic distribution of force loading of grove milling

The 40 passes were performed for each tested milling cutters (coated and uncoated). 1st, 10th, 20th, 30th, and 40th passes were measured by Dynamometer Kistler.

The secondary monitored parameter was tool wear – exactly flank wear measured by tool microscope Alicona (criterion VB was used – see Fig. 5).

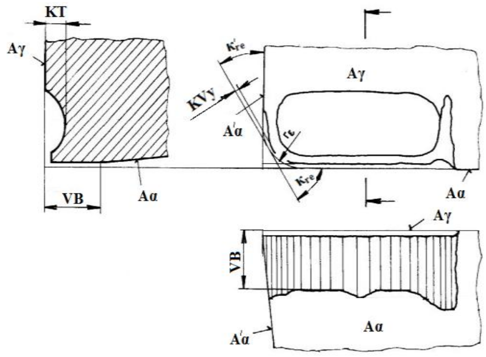

Figure 5. Tool wear criterions [Forejt 2003]

The experimental procedures were considered to completed if the value of the criterion VB reached a value of VB=0.2 mm where a maximum of 40 passes were made even if the limit criterion has not been achieved.

3 RESULTS

The first was tested uncoated milling cutter then all coated milling cutters. Forty passes (cuts) were performed by each tested tools which represents machining time t=24.5 min.

3.1 Force loading

The monitored parameters were the values of cutting force of groove milling at the beginning (1st cut) and at the end of machining (40th cut). The best result (after 1st cut) was achieved with milling cutter with PVD coating (Al,Ti)N, the worst result with the uncoated cutting tool.

The lowest value of cutting force at the end of machining (after 40th cut) was achieved with the tool with PVD coating (Al,Ti)N and the highest value with uncoated milling cutter. These results were predicted, because PVD coatings extend the tool life and reduce the cutting forces during machining, in our case during groove milling. Time series of the force loading (Fc, FcN, Fp, F) during groove milling for uncoated milling cutter is shown in Fig. 6 and for the tool with PVD coating (Al,Ti,Cr)N in Fig. 7. It is obvious that with increase flank wear increases the force load of the tool (see in Fig. 6) and this causes higher energy demands. The reached values of cutting forces for all tested tools are shown in Tab. 4.

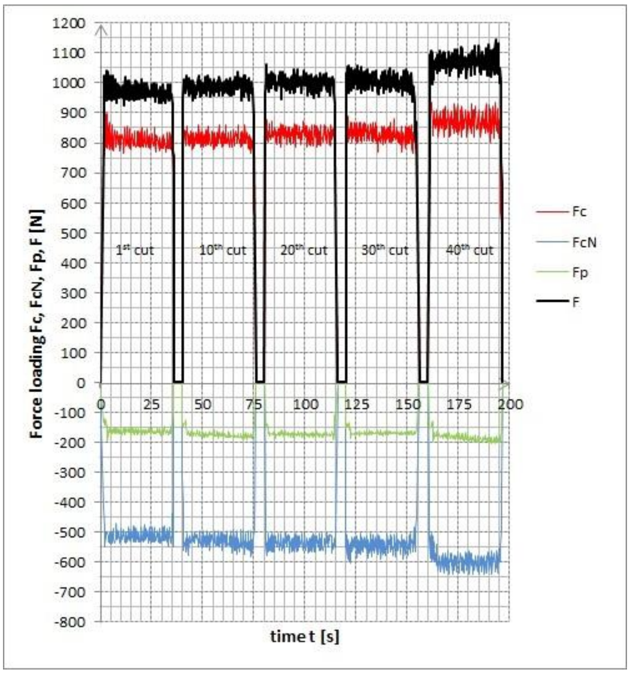

Figure 6. Time series of the force loading for uncoated milling cutter

The y-axis (Fig. 6 and Fig. 7) does not correspond to the real machining time that was 24.5 min.

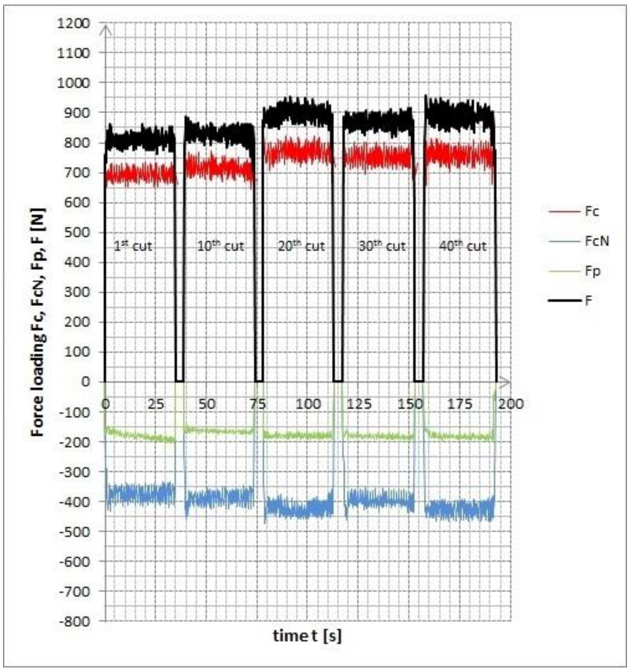

Figure 7. Time series of the force loading for coated milling cutter with (Al,Ti,Cr)N PVD coating.

The relative (percentage) increase of cutting forces was more important to observe. The best result was achieved with the tool with PVD (AL,Ti,Cr)N coating, there was only 6.91% increase. The uncoated milling cutter reached 9.34% increase of cutting force during groove milling (second-best result) which was smaller compared to the milling cutters with PVD coating (Al,Ti)N and with PVD nanocomposite coating nACo. Only the tool with nanocomposite coating achieved more than 10%. Increase of mean Fc for all tested tools was not so bad, because tools were in the cut for about 25 minutes. All reached values of relative increase of cutting forces are shown in Tab.4.

The values of cutting force in a particular point in time for all tested milling cutters are shown in Fig. 8. The continuous increase of cutting forces can be observed for all tested milling cutters. Regression equations are shown for immediate detection of value of cutting force at a given time.

Cutting tool	Mean Fc (1st cut) [N]	Mean fc (40th cut) [N]	Increase of mean Fc [N]	Relative increase of Fc [%]
Uncoated	803	878	75	9.34
nACo	705	801	96	13.62
(Al,Ti)N	679	745	66	9.72
(Al,Ti,Cr)N	709	758	49	6.91

Table 4. The mean value of cutting force Fc during groove milling

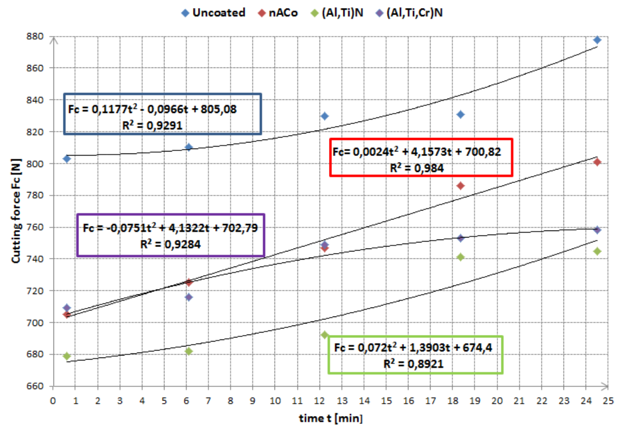

Figure 8. The values of Fc in a particular point in time

3.2 Flank and face wear of milling cutters

Another very important measurement parameter was flank wear. The value of flank wear was measured with the tool microscope Alicona IF G4. Flank wear was measured (for each 10th cut) on all three edges and was observed as mostly uniform. The maximum value of flank wear VB was set up to VB=0.2 mm which was not reached by all tested milling cutters, because only 40th passes were performed. Comparison of flank wear for all tested tools is shown in Fig. 9.

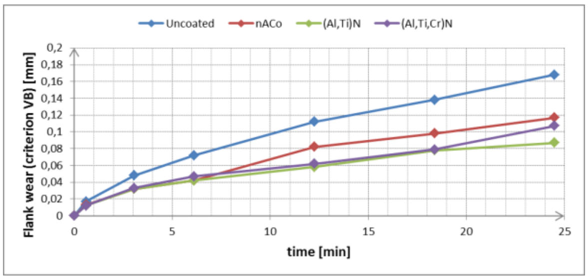

Figure 9. Comparison of flank wear of tested un/coated milling cutters

As expected, the maximal value of criterion VB was achieved with uncoated cutting tool (VB=0.168 mm), the lowest with tool with PVD coating (Al,Ti)N (VB= 0.087 mm). It is commonly known that PVD (or CVD) coatings increase the tool life which was verified in the experiment. Reached values of flank wear at the end of machining are shown in Tab. 5.

Cutting tool	Uncoated	nACo	(Al,Ti)N	(Al,Ti,Cr)N
VB [mm]	0.168	0.117	0.087	0.107

Table 5. Reached values of flank wear after groove milling

The wear mechanism was analyzed with light and the electron microscopy. Predominantly abrasive wear with different intensity was observed on all tested milling cutters (the highest on uncoated tool). It is obvious that all tested tools are partly worn (on flank and face) and they could work at higher cutting and feed speeds. Face wear (light microscopy) for all tools are shown in Fig. 10. Electron microscopy was used for identifying the flank and face wear for coated tools (see Fig. 11-13).

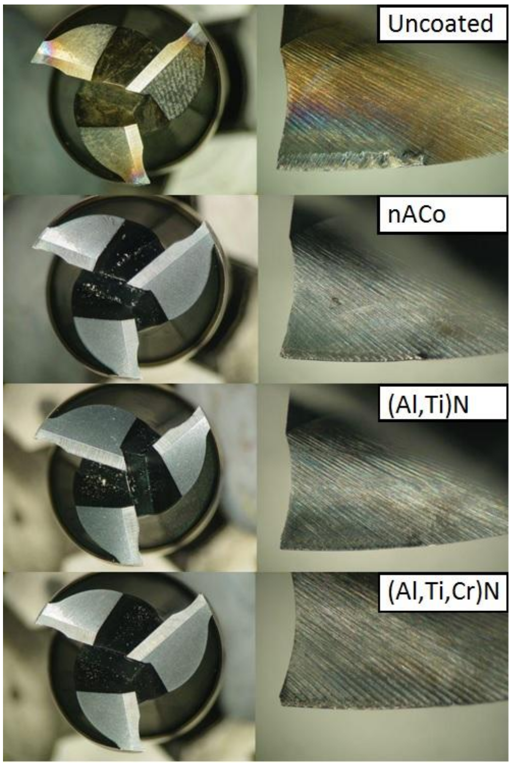

Figure 10. Face wear of all tested milling cutters (light microscopy)

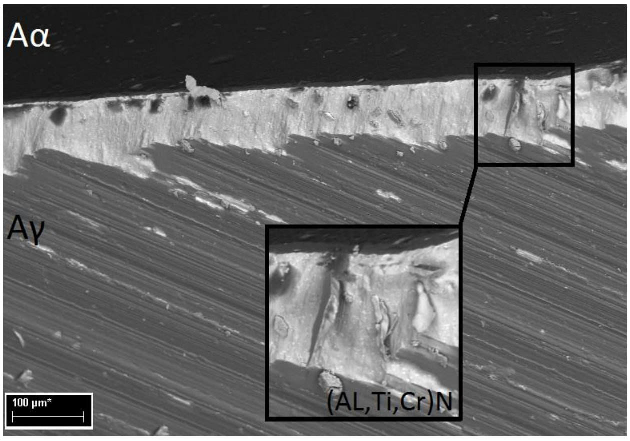

Figure 11. Flank and face wear of HSS milling cutter with PVD (Al,Ti,Cr)N coating (BSE)

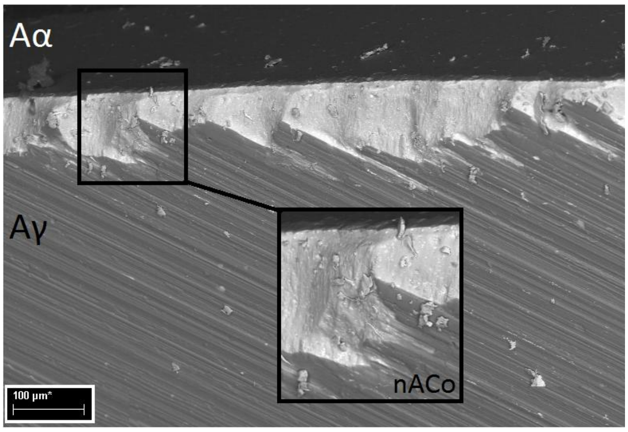

Figure 12. Flank and face wear of HSS milling cutter with nanocomposite PVD nACo coating (BSE)

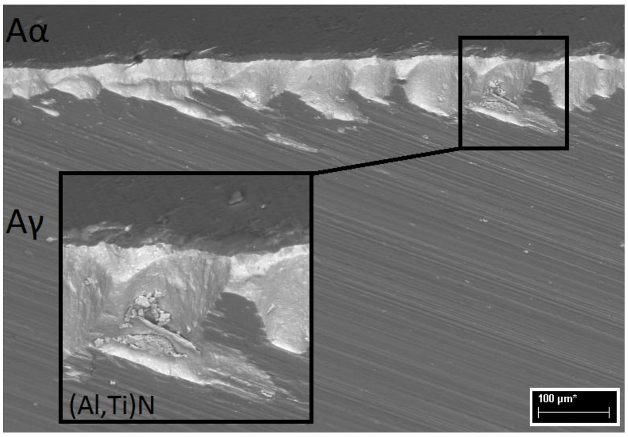

Figure 13. Flank and face wear of HSS milling cutter with PVD (Al,Ti)N coating (BSE)

3.3 *Surface quality analysis*

Surface quality analysis is a very important parameter in manufacturing technology. Machined surfaces (1st, 10th, 20th, 30th, and 40th cut) were measured by Surtronic S128 roughness meter. Each machined surface was measured three times and their mean was used (parameters Ra and Rz). Arithmetical mean height Ra= 3.2 µm was set up as a maximum value.

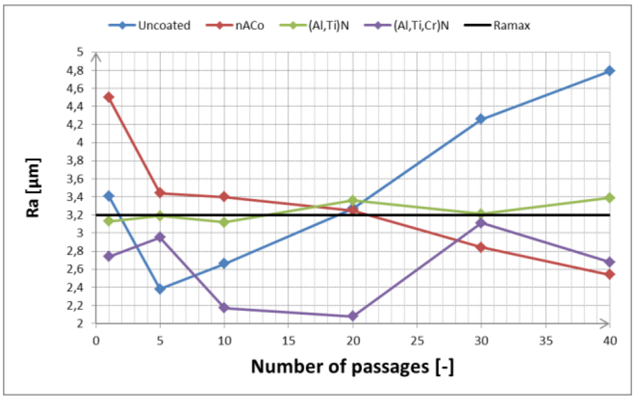

Figure 14. Arithmetical mean height for measured passages for each tested milling cutter

Only milling cutter with PVD coating (AL,Ti,Cr)N fulfilled the set up condition (Ra= 3.2 µm) throughout the machining process. The values of Ra were almost constant for cutting tool with PVD (Al,Ti)N coating and moved around the maximum value throughout milling process . The worst results were achieved with uncoated milling cutter (see Fig. 14). Maximum height of profile Rz was supplementary measurement (see Fig. 15) and example of output data are shown in Fig. 16. Jumping change of Ra and Rz through machining can be explained by the fact that the workpiece contained many inclusions and also workpiece clamping could have an impact of these jump change.

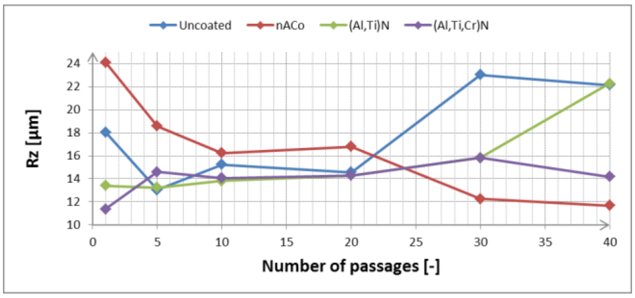

Figure 15. Maximum height profile for measured passages for each tested milling cutter

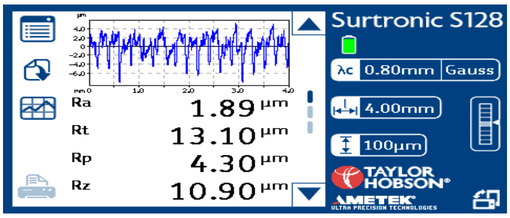

Figure 16. Example of output data from the Surtronic S128

4 CONCLUSIONS

Based on the force load, flank and face wear and surface quality analysis of the experimental groove milling of tool steel DIN 90MnCrV8 (usually called as a Stabil steel) the following conclusions for the uncoated and coated HSS milling cutters can be made:

- all tested HSS milling cutters reached 40 passes what represents the machining time 24.5 minutes for the cutting conditions,
- the lowest relative increase of cutting force Fc was achieved with milling cutter deposited by PVD (Al,Ti,Cr)N coating (6.91%),
- the highest relative increase of cutting force Fc was achieved with milling cutter deposited by PVD nanocomposite coating nACo (13.62%), which was almost two more times than the tool with (Al,Ti,Cr)N coating,
- the milling cutter with nACo coating also confirmed an increased cutting performance, especially compared to the uncoated HSS milling cutter,
- all tested cutting tools have not exceeded the maximum value of criterion VB=0.2 mm, the highest value reached the uncoated cutting tool (VB= 0.168 mm), the lowest value reached milling cutter with PVD coating (Al,Ti)N (VB=0.087 mm) – approximately half value in compare with uncoated tool,
- in general PVD coatings increase the tool life that was verified of the experiment,
- equal flank and face wear was observed on all three teeth,
- the partial flank and face wear on all tested milling cutters with PVD coatings can be observed, which have been made by abrasive mechanism predominantly and by adhesive mechanism (especially on the tool deposited by PVD coatings based on Al and Ti),
- only the milling cutter with PVD (Al,Ti,Cr)N coating fulfilled set up value of arithmetical mean height Ra=3.2 μm throughout machining, the worst results were achieved with uncoated cutting tool,
- the milling cutter with PVD coating (Al,Ti)N showed almost constant value arithmetical mean height which moved around the value Ra=3.2 μm,
- the HSS milling cutters with PVD coatings proved also to work at higher cutting and feed speeds what is a subject of the next research.

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